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A New Receiver for a Digital Passband System with CPSK Modulation: The STTS-CPSK Receiver

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Telecommunications industry is expanding vastly with huge infrastructure requiring huge sums of money for investment[1,2]. Reliability of the system[3,4], efficient utilization of resources[1,2], and safety of the users and the environment are paramount towards providing high quality efficient telecom services at affordable prices[1,2]. This paper deals with an important scientific investigation for the development of the STTS-CPSK receiver for pass band applications[5,6] . This is a new receiver being developed with the inspiration from the previously developed STTS-MF receiver for baseband applications. This is carried out considering transmission of ***p-q*** signals (***p-q*** signals represent correlated digital signals) through AWGN channel. Performance-comparison studies of the conventional STS-CPSK receiver and the new STTS-CPSK receiver are carried out for a wide range of signal and system parameters $0.0 \leq p,q \leq 1.0$ and-10 dB $\leq SNR \leq$ 10 dB. Performance superiority of the STTS-CPSK receiver is established for $0.0 \leq p,q \leq 1.0$, -2 dB $\leq SNR \leq$ 10 dB, and illustrated. Thus, this work has important implications towards efficient utilization of bandwidth, and also in greening of communication technologies which is highly needed. The latter is because the performance-improvement, achieved in case of STTS-CPSK receiver, can be translated into an equivalent advantage of EMF-reduction appropriately.

Keywords: Green Technology, Signal De-noising, Signal correlations, Bit error rate, ***p-q*** signals, Performance and QoS, Simulation, Coherent PSK receiver, Communications Signal Processing, Stochastic Signal Processing

Introduction

In[7-11] authors have developed two better performing new receivers, the STTS-MF receiver and the CTTS-MF receiver for baseband applications, applicable when ***p-q*** signals are transmitted through AWGN channel and the correlation parameters p, q are known at the receiver. The terminology is explained in[7-11]. Application of this to the case of wireless is very important[12]. When the STTS-MF concepts are applied to a wireless system with CPSK modulation, the resulting receiver is termed as the STTS-CPSK receiver. Using extensive simulation study and analysis, the performance evaluation and comparison study of the STTS-CPSK receiver and the STS-CPSK receiver (conventional receiver with Matched Filter) is carried out, considering a wide range of signal and system parameters $0.0 \leq p,q \leq 1.0$, -10 dB $\leq SNR \leq$ 10 dB. As an outcome, it is observed that the performance of the STTS-CPSK receiver is superior to that of the conventional STS-CPSK receiver for -2 dB $\leq SNR \leq$ 10 dB, $0.0 \leq p,q \leq 1.0$.

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Conventional STS-CPSK receiver: A brief review

BPSK (Binary-Phase-Shift-Keying) is one of the widely used digital carrier (pass-band) modulation scheme. It is extensively used in both wired and wireless communication networks, including mobile and satellite communication[5,6]. Mathematically, the BPSK signals can be expressed as[5,6];

Corresponding to bit 1, transmit $S_1(t) = A.\cos(2\pi f t)$; for $0 \leq t \leq T_b$

Corresponding to bit 0, transmit $S_2(t) = A.\cos(2\pi f t + \pi)$; for $0 \leq t \leq T_b$ ...(1)

In Eq. (1), A and f are amplitude and frequency respectively of the modulated carrier, and, T_b represents the bit duration. Thus, in BPSK, corresponding to a bit 1, carrier signal is transmitted without any phase shift, while, corresponding to a bit 0, carrier signal is phase shifted by 180^o or π radians. The other way is also possible. Since, in this, binary information is transmitted in the carrier phase, the scheme is referred to as Binary-Phase-Shift-Keying (BPSK) or simply PSK (Phase Shift Keying)[5,6]. Block diagram of BPSK transmitter can be referred from[5,6]. As mentioned earlier, the information transmitted through communication channel gets corrupted by the channel noise. The design objective of communication receiver is to recover the information from its corrupted version, in an efficient manner. One such receiver is the Matched filter based receivers as shown in Figure1 for BPSK modulation. It was shown in[5,6] that, for the transmission of uncorrelated digital signals (referred to as $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signals in[7-12]) through stationary Additive-White-Gaussian-Noise (AWGN) channel, the MF based BPSK receiver (refer to Figure 1) does optimal detection in terms of minimized Bit-Error-Rate at the receiver output[5,6]. Since, in this (refer to Figure 1), carriers used at the transmitter and at the receiver are assumed to be in phase and frequency coherence, the receiver is termed here as Matched-Filter-based-Coherent P SK receiver (MF-CPSK receiver). As can be seen from Figure1, the MF-CPSK receiver comprises of a Matched filter, a sampler and a Decision Device (DD). The Matched filter (MF) output is sampled at an optimum sampling instant, $t = T_b$, and compared with a threshold (λ) in DD[5,6]. For $y \geq \lambda$, DD produces bit a 1 else a bit 0 is produced at its output. It is important to mention here that the role of threshold (λ) is critical in the design of an optimum receiver[5,6]. An appropriately designed threshold usually results in minimum *BER* at the receiver output. Such a threshold is referred to as an optimal threshold (λ_{opt})[5,6]. With the logic as described in[6], the expression of optimum threshold in MF-CPSK receiver, for the transmission of uncorrelated $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signals through stationary AWGN channel with PSD (Power Spectral Density) $N_0/2$, can be written as[6]:

$$\lambda_{STS-CPSK-opt-uc} = \frac{N_0}{4\sqrt{E}} ln\left(\frac{r_0}{r_1}\right) \qquad \text{... (2)}$$

In the subscript of λ, the terms '*STS*' is the name of receiver, '*opt*' and '*uc*' are to indicate that the threshold is optimal for uncorrelated digital signals. In Eq. (2), $N_0/2$ is the Power-Spectral-Density (PSD) of white noise; r_0, r_1 are the independent probabilities of a bit to be 0 or 1 respectively, and, E is the average energy per bit, that is, $E = r_0 * E_0 + r_1 * E_1$ with E_0, E_1 being the energies corresponding to signals $S_1(t)$ and $S_2(t)$ respectively (refer to Eq. (1)). As, in this receiver (refer to Figure 1), the bit detection is based on the use of a single threshold ($\lambda_{STS-CPSK-opt-uc}$), the receiver is referred to here as Single-Threshold-Scheme-based-Coherent-PSK receiver (STS-CPSK receiver). It is to be noted here that now onwards, throughout the paper, the conventional Matched filter based CPSK receiver will be referred to as 'STS-CPSK receiver'. Validation study concerning optimality of STS-CPSK receiver for $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signals has been carried out by the authors. However, because of page limitations, the corresponding results have not been shown here.

Limitation of the STS-CPSK receiver and development of the STTS-CPSK receiver

As mentioned in the previous section, the STS-CPSK receiver is optimal for the case when uncorrelated $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signals are transmitted through stationary AWGN channel. However, as discussed in[7-11], many situations and applications do exist in which rather than uncorrelated $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signals, the transmitted digital signals are correlated in nature[7-11]. Thus, if rather than uncorrelated $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signals, the transmitted digital signals are correlated ***p-q*** in nature then, it raises following important questions that need to be answered appropriately through research, i) Does the STS-CPSK receiver still remain optimal? ii) If not, is it possible to develop a new improved receiver with performance better than that of the conventional STS-CPSK receiver? iii) If the answer is 'yes', what would be structure and functional characteristics of such receiver? How such receiver would be developed? These questions have been answered successfully in this paper in the following ways: i) Firstly it is explained that, for the transmission of ***p-q*** signals through stationary AWGN channel, the STS-CPSK receiver does not remain optimal, ii) A new improved receiver, termed here as the STTS-CPSK, is developed, suitable for the transmission of ***p-q*** signals. These have been carried out as follows. As mentioned in the previous section, the STS-CPSK receiver uses a single threshold (as given by Eq. (2)) for the detection of uncorrelated $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signals. In Eq. (2), for a given N_0 and E, the threshold of STS-CPSK receiver ($\lambda_{STS-CPSK-opt-uc}$) is a logarithmic function of ratio of independent bit probabilities (r_0/r_1). Here r_0 can be seen as the probability that occurrence of next bit is going to be 0 while, r_1 is the probability that occurrence of next bit is going to be 1. Since, for the case of ***p-q*** signals, the occurrence of next bit depends on the nature of previously generated bit, thus, the knowledge of previously detected bit can help in improving the detection of the present bit. Or to say, for the transmission of ***p-q*** signals through AWGN channel, the STS-CPSK receiver becomes sub-optimal. This is the limitation of STS-CPSK receiver which we want to overcome by developing the STTS-CPSK receiver. The development of the STTS-CPSK receiver is carried out as follows. In the development of STTS-CPSK receiver, it is assumed that the probability of newly occurring bit to be 0 or 1 depends on the nature of previously detected bit. Thus, the ratio *Pr(the newly occuring bits is 0)/Pr(the newly occuring bits is 1)*, can be seen to be dependent on the nature of the previously recovered bit, unlike in the case of $\boldsymbol{r_0}$-$\boldsymbol{r_1}$ signal. This implies that the threshold value also can be considered to be dependent on the previously recovered bit. Hence, for the case of ***p*-*q*** signals, two thresholds are possible, one is valid when the previously recovered bit is 0, while, the other is applicable when the previously recovered bit is 1. These two thresholds are derived analytically as follows:

Case-0: This case arises when previously recovered bit at the receiver is 0. In such a case the probability that the next bit would be '0' is assumed as 'p' instead of 'r_0', in the expression for threshold $\lambda_{STS\text{-}CPSK\text{-}opt\text{-}uc}$ of Eq. (2). And similarly, the probability that the next bit would be 1 is assumed to be '$1 - p$' instead of 'r_1' in the same expression. Using this, the new threshold corresponding to the case when previously recovered bit is 0, can be obtained by simply replacing r_0 with p, and r_1 with $1 - p$ in the r.h.s. expression of Eq. (2). The corresponding threshold is termed as $\lambda_{STTS-CPSK-c0}$ and is given by following expression:

$$\lambda_{STTS-CPSK-c0} = \frac{N_0}{4\sqrt{E}} ln\left(\frac{p}{1-p}\right) \quad ...(3)$$

In subscript of Eq. (3), *'c'* indicates the correlated digital signals, '0' indicates the case of previously recovered bit is 0, and, STTS is the name of receiver.

Case-1: This case arises when previously recovered bit at the receiver is 1. In such a case, the r_0 and r_1 of Eq. (2) can be replaced by $1 - q$ and q respectively by using similar lines of argument as above, and the corresponding threshold, represented as '$\lambda_{STTS-CPSK-c1}$' becomes:

$$\lambda_{STTS-CPSK-c1} = \frac{N_0}{4\sqrt{E}} ln\left(\frac{1-q}{q}\right) \quad ...(4)$$

Thus, working of the STTS-CPSK receiver involve the use of two-thesholds, $\lambda_{STTS-CPSK-c0}$ and $\lambda_{STTS-CPSK-c1}$, according to Eqs. (3) and (4), depending upon whether the previously recovered bit is 0 or 1 respectively. On the other hand, classical way is to use the STS-CPSK receiver with single threshold $\lambda_{STS-CPSK-opt-uc}$ as given in Eq. (2). In STTS-CPSK receiver, the detection of new bit is decided by comparing the sampled output of matched filter (y) (refer to Figure 1) with one of the two thresholds, that is, $\lambda_{STTS-CPSK-c0}$, when previously recovered bit is 0, and, $\lambda_{STTS-CPSK-c1}$ when previously recovered bit is 1. If the sampled value of the matched filter output is greater than or equal to the appropriate threshold, DD produces bit 1, else bit 0 is detected as a recovered new bit. Using extensive simulation, it is shown in the succeeding section that the STTS-CPSK receiver performs substantially better than the classical STS-CPSK receiver for $0.0 \le p, q \le 1.0$ and for the limited values of SNR in the range -2 dB $\le SNR \le$ 10 dB. While for $SNR < -2$ dB, the perfromance of STTS-CPSK is found to be inferior to that of the conventional STS-CPSK receiver.

STTS-CPSK and STS-CPSK: Performance evaluation and comparison study

Once the STTS-CPSK receiver is developed as outlined above, it is important to evaluate its performances and compare with that of the conventional STS-CPSK receiver. This is the objective of this section. For the performance-evaluation and comparison study, the following performance-improvement parameter is defined and used:

$$PRBER_{STS-CPSK}^{STTS} = \left(1 - BERRF_{STS-CPSK}^{STTS}\right) * 100 = \left(1 - \frac{BER_{STTS-CPSK}}{BER_{STS-CPSK}}\right) * 100 \quad ...(5)$$

Here, in Eq. (5), $BER_{STTS-CPSK}$ and $BER_{STS-CPSK}$ are the Bit-Error-Rates (*BERs*) at the output of STTS-CPSK and STS-CPSK receivers respectively while considering same set of signal parameters. $PRBER_{STS-CPSK}^{STTS}$ is the gain by STTS-CPSK receiver over STS-CPSK receiver. Performance evaluation and

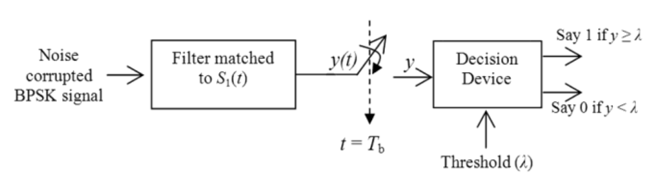

Fig. 1 — Block diagram of the MF-CPSK receiver[5,6]

comparison study is carried out with the help of following experimentations.

Variation of performance-improvements with SNR

For performance evaluation study, various experimentations are possible. In line with previous studies[7-12], one experimentation for example is, for the given (p, q) pair values, evaluate the performance of both STTS-CPSK and STS-CPSK receivers, and plot with *SNR* varying in the range -10 dB ≤ *SNR* ≤ 10 dB. This can be done for the following two cases a) when $p = q$, b) when $p \neq q$. The ***p-q*** signals generated with $p = q$ are special class of ***p-q*** signals which corresponds to $r_0 = r_1 = 0.5$ (here, r_0 is the probability of a given transmitted bit is 0, and r_1 is the probability that a given transmitted bit is 1, in the transmitted ***p-q*** signal), which is found as well as desired in many applications[7-12]. Figures 2(a) and 2(b) show the $PRBER_{STS-CPSK}^{STTS}$ vs. *SNR* curves corresponding to the (p, q) pairs values of (0.05, 0.05), (0.1, 0.1), (0.2, 0.2), (0.75, 0.75) when $p = q$, and, (0.02, 0.08), (0.15, 0.05), (0.30, 0.10), (0.80, 0.70) when $p \neq q$. In both the cases, the selected (p, q) value pairs have same $p + q$ values. From Figures 2(a) and 2(b), following observations can be drawn:

- Corresponding to all the considered (p, q) pair values, for both the cases of $p = q$ (refer to Figure 2(a)) and $p \neq q$ (refer to Figure 2(b)), a substantial improvement by STTS-CPSK receiver over the conventional STS-CPSK receiver is observed for *SNR* ≥ -2 dB. Maximum value of $PRBER_{STS-CPSK}^{STTS}$ is observed as 60% (approximately), for both the cases of $p = q$ (refer to Figure 2(a)) and $p \neq q$ (refer to Figure 2(b)), corresponding to $p + q = 0.1$, *SNR* ≥ 6 dB. This indicates 60% reduction in *BER* by STTS-CPSK receiver over the conventional STS-CPSK receiver.
- For *SNR* ≥ -2 dB, corresponding to both the cases of Figure 2(a) and Figure 2(b), the performance-improvement is seen to increase almost linearly with increase in *SNR*, till *SNR* = 6 dB. While for *SNR* ≥ 6 dB, it is observed that the performance-improvement stagnates, does not increase further. This linearity of the performance-improvement curve has many advantages including development of an efficient analytical model for the prediction of performance-improvement, for given p, q and *SNR* values as was attempted in[9]. Carrying out the same for $PRBER_{STS-CPSK}^{STTS}$ can be considered as a future extension to this work.
- For a given (p, q) pairs values and *SNR*, almost similar performance-improvement is observed corresponding to both the cases when $p = q$ (refer to Figure 2(a)) and $p \neq q$ (refer to Figure 2(b)). Further, for *SNR* ≥ -2 dB, for both the cases of Figure. 2(a) and Figure 2(b), higher performance-improvement is observed corresponding to lower $p + q$ values and, the performance-improvement is found to decrease as $p + q$ increases towards 1.0. This indicates dependence of the performance-improvement on the sum $p + q$, rather than on p, q values. The similar dependence of the performance-improvement by the TTS-MF receiver over the conventional STS-MF receiver

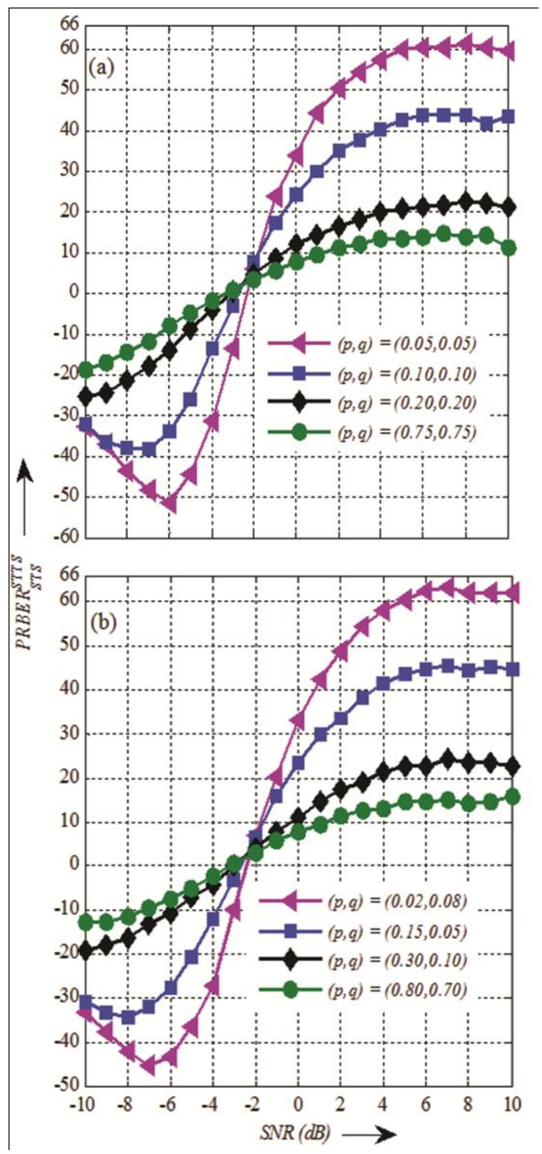

Fig. 2 — $PRBER_{STS-CPSK}^{STTS}$ vs. *SNR* plots corresponding to different (p, q) pair values a) when $p = q$, b) when $p \neq q$.

was observed in[7-9] and detailed study concerning this was carried out in[9] for the baseband case. This dependence of performance-improvement, $PRBER_{STS-CPSK}^{STTS}$ on the sum p + q requires detailed investigation which is not a part of this work.

- For lower values of *SNRs*, *SNR* < -2 dB, it is observed that the performance of newly developed STTS-CPSK receiver is worse than that of conventional STS-CPSK receiver. Thus, for given (p, q) pair values, the STTS-CPSK receiver work better-than the STS-CPSK receiver for the range, *SNR* ≥ -2 dB. In other words, *SNR* ≥ -2 dB is the 'Green region' of operation for the STTS-CPSK receiver.

Variation of performance-improvements with p (or q) keeping (r_0, r_1) fixed

Another experiment can be, for a given *SNR*, observe and plot the variation of performance-improvement with correlation parameters p, q, keeping r_0, r_1 fixed*. This experiment is in line with the one carried out in[7-12]. The detailed explanation concerning objective and method used for this experiment can be referred from[7-12]. Figure 3 and Figure 4 show variation of the performance-

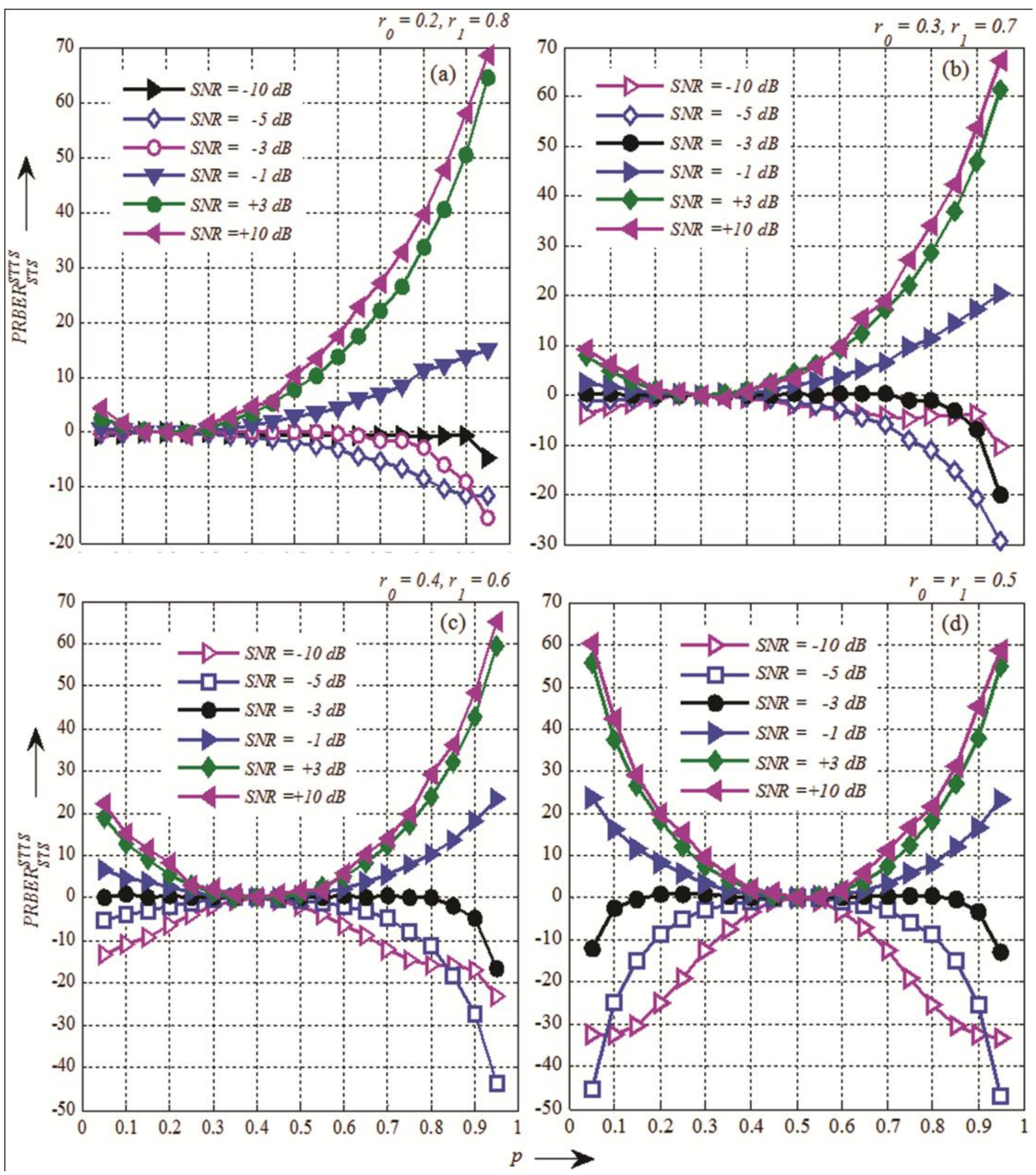

Fig. 3 — $PRBER_{STS-CPSK}^{STTS}$ vs. p curves corresponding to (r_0, r_1) pair values of a) (0.2, 0.8), b) (0.3, 0.7), c) (0.4, 0.6), d) (0.5, 0.5).

improvement ($PRBER^{STTS}_{STS-CPSK}$) with p, for following (r_0, r_1) pair values: (0.2, 0.8), (0.3, 0.7), (0.4, 0.6), (0.5, 0.5). Fig. 4 shows the $PRBER^{STTS}_{STS-CPSK}$ vs. q curves corresponding to (r_0, r_1) pair values of (0.6, 0.4), (0.7, 0.3) and (0.8, 0.2). From results of Figure 3 and Figure 4 following conclusions can be drawn:

- As can be seen from Figure 3 and Figure 4, for a given (r_0, r_1) pair values, corresponding to $SNR \geq -3$ dB, $PRBER^{STTS}_{STS-CPSK} > 0$ is observed for all the considered p, q values in the range $0.0 < p,q < 1.0$, except at $p = r_0$ (refer to Figure 3), and, except at $q = r_1$ (refer to Figure 4) for which $PRBER^{STTS}_{STS-CPSK} = 0$. Also, higher performance-improvement is observed corresponding to the higher or the lower p, q values (refer to Figure 3 and Figure 4).
- For (r_0, r_1) pair and the corresponding several (p, q) pair values values, higher performance-improvement is observed corresponding to higher SNR values. Performance-improvement as high as 70% (approx.) reduction in BER, indicated by $PRBER^{STTS}_{STS-CPSK} = 70$, is observed corresponding to $r_0 = 0.2$, $r_1 = 0.8$ (refer to Figure. 3(a)), $r_0 = 0.3$, $r_1 = 0.7$ (refer to Figure 3(b)), and, $r_0 = 0.8$, $r_1 = 0.2$ (refer to Figure3(c)), at $SNR = 10$ dB. This is a substantial-improvement and makes this work suitable for 'Greening of Communication Technology'. This is because, as discussed in[7,8], reduction in BER, as achieved here, can be translated into equivalent advantage of reduction in EMF exposure to the living beings[7,8]. To explain this further, let us refer to Figure 3 of[7] (at page number 154), corresponding to $p = q = 0.9$ considering baseband modulation[7]. As can be seen from Figure 3 of[7], BER improvement is translated into equivalent reduction of transmitted SNR. This reduction in SNR is converted into the equivalent signal power requirement reduction factor ($SPRRF$). $SPRRF$, calculated for different (p, q) pair values and SNR, are shown in Figure. 6 of[7] (refer to page number 157 of[7]). Reduction in the signal power requirement leads to reduction in transmitted EMF intensity (for both baseband as well as passband) thus improving the safety to living beings. This is how this work has important implication for safety of living beings through greening of communication technology. What is shown to be achieved in the case of baseband communications can in principle be shown to be achieved in the case of passband communications, in the same way as shown in[7].

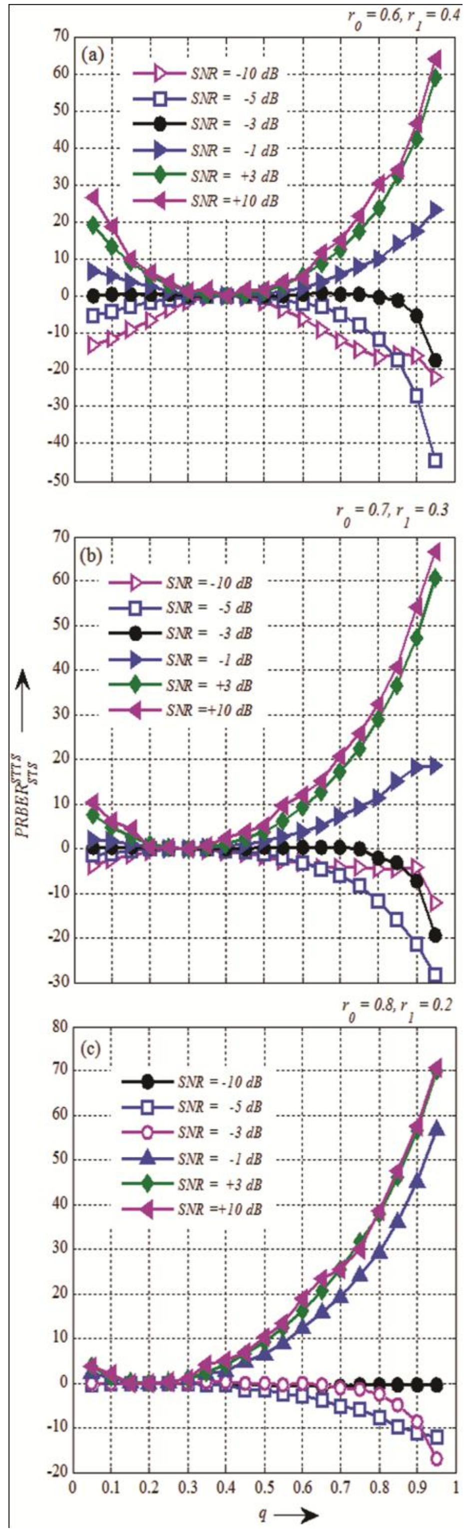

Fig. 4 — $PRBER^{STTS}_{STS-CPSK}$ vs. q curves corresponding to (r_0, r_1) pair values of a) (0.6, 0.4), b) (0.7, 0.3), c) (0.8, 0.2).

- For a given (r_0, r_1) pair values and SNR, $PRBER_{STS-CPSK}^{STTS}$ vs. p curve for p = r_0 + ε is almost same as $PRBER_{STS-CPSK}^{STTS}$ vs. p curve for p = r_0 – ε (refer to Figure 3(a) to 3(d)), where ε is a small variation or change. Similarly, $PRBER_{STS-CPSK}^{STTS}$ vs. q curve corresponding to q = r_1 + ε is almost same as $PRBER_{STS-CPSK}^{STTS}$ vs. q curve for q = r_1 - ε (refer to Figure 4(a) to 4(c)). This symmetrical nature of $PRBER_{STS-CPSK}^{STTS}$ vs. p curves (around p = r_0) and $PRBER_{STS-CPSK}^{STTS}$ vs. q curves (around q = r_1) is more clear from Figure 3(d), corresponding to r_0 = r_1 = 0.5. Further, corresponding to r_0 = r_1 = 0.5, $PRBER_{STS-CPSK}^{STTS}$ vs. p and $PRBER_{STS-CPSK}^{STTS}$ vs. q become same. This is because, as explained in[7,8] p become equal to q at r_0 = r_1 = 0.5.
- Substantial performance-improvement of approximately 60% reduction in *BER* is observed corresponding to the case when r_0 = r_1 = 0.5, at *SNR* = 10 dB. This is an important result since r_0 = r_1 = 0.5 is desired in many applications, for the efficient clock recovery of information bits at the receiver[7,8].
- For the considered (r_0, r_1) pair values, corresponding to lower values of *SNR* in the range, SNR < -3 dB, $PRBER_{STS-CPSK}^{STTS} < 0$ is observed for both $PRBER_{STS-CPSK}^{STTS}$ vs. p and $PRBER_{STS-CPSK}^{STTS}$ vs. q curves of Figure 3 to Figure 4. That is performance of STTS-CPSK receiver is inferior to that of the conventional STS-CPSK receiver for *SNR* < -3 dB. Thus, green region of operation for STTS-CPSK receiver is *SNR* > -3 *dB*. This result is in agreement with the results of Figures 2(a) and 2(b).

Conclusions

A new receiver, the STTS-CPSK, is developed and compared in performance with that of the conventional STS-CPSK receiver. Performance evaluation and comparison study of these receivers are carried out with the help of different, useful experiments. This is done for the case when correlated ***p-q*** signals are transmitted through AWGN channel, when p, q values are known at the receiver. Corresponding to the values of *SNR* in the range, -2 dB ≤ *SNR* ≤ 10 dB, performance of the STTS-CPSK receiver is found superior to that of the conventional STS-CPSK receiver, while, for *SNR* < -2 dB, the performance of the STTS-CPSK receiver is found to be inferior to that of the STS-CPSK receiver. This is observed for all the considered p, q, r_0 and r_1 values. Maximum $PRBER_{STS-CPSK}^{STTS}$ of about 70 is observed corresponding to *SNR* = 10 dB. This is a substantial improvement and can be useful for 'Greening of Communication Technology', as explained and demonstrated in[7,8]. Quantitative analysis concerning increase in safety (in terms of reduced transmission EMF) by the use of STTS-CPSK receiver over STS-CPSK receiver, and, dependence of the performance-improvement on *SNR*, sum p + q can be important possible future extensions to this work.

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